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DC Superconducting Cables*

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ABSTRACT

Progress in the development of dc superconducting cables suggests these systems will provide an attractive alternative among cable options where long lengths of high-capacity underground transmission lines are required. Here we discuss the general characteristics of dc superconducting cables as well as details of two specific designs, one coaxial and the other double monopolar. The special advantages of these cables lie in the relative simplicity of construction, their extremely high operating efficiency, and their compactness when compared with other ac or dc high-capacity cables cooled by flowing fluids, either at ambient or cryogenic temperatures. These features are discussed in the context of economic, environmental, and power system considerations, including some of the possible trade-offs among conventional and superconducting ac and dc systems.

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Section 1
INTRODUCTION

The only valid reason for pursuing the development of superconducting power transmission cables arises from the assumption, or belief, that high-capacity underground electric power lines will be required in the US grid. While the meaning of "high-capacity" is crucial here, it is also somewhat ambiguous; but we can, for our purposes, interpret it to indicate quite generally the range of capacities now beyond present technology, perhaps 5 GW and above, in a single circuit. Equally crucial is the time frame in which this need will occur and the growth rate in the number of cable-miles that could be expected. In the early 1970s, when the US was increasing its electric power consumption at about 7% per year, it was not unreasonable to project this need for high capacity cables to be felt by 1990, or 2000 at the latest. Now, in the late 1970s, with annual consumption increases running at less than half the earlier rate, we should probably add several decades to our target date. Some may argue that it should be postponed indefinitely, as the trend in power planning should be towards dispersed power generation rather than toward the power-park concept that underlies the assumption for high-capacity cable requirements.

Our own view is that the US power generation heirarchy will encompass the very large and the small production sites, that the large plants or parks will usually be situated well away from urban centers, and that sometime not too long after the year 2000 high capacity lines of significant lengths will be required. For such a mission, it is not at all clear that mere extension of present cable technology will do the best job - or even an adequate job - nor should the industry or the nation settle for that solution without investigating new, alternative technologies. Because considerable careful research and extensive testing over a long time are necessary before a new, perhaps radical, technology can be developed and proven to meet the exacting reliability criteria of the industry, we feel it is not too early to be working concentratedly on any new cable technology having promise of superior performance.

One such technology, we feel, is that employing superconductivity. Since about 1967, superconducting power transmission line (SPTL) development has been carried out on varying levels in such countries as West Germany, England, France, Austria, Japan, USSR and the US. After about 1975 activity in these programs in the geographically smaller nations slowed considerably or ceased entirely, primarily because the need for high-capacity cables was judged too far in the future for these nations. Similar considerations have affected the SPTL programs in the US, where in 1975 five laboratories were at work on this technology and in 1980 there will be but one. On the other hand, the USSR program is several times larger than that of the US and apparently continues to expand.

The one remaining US SPTL program will be that at Brookhaven National Laboratory (BNL), where a facility for demonstrating an alternating current (ac) SPTL is well under way. On the other hand, this paper is to deal with direct current (dc) SPTL, an area in which, until recently, the Los Alamos Scientific Laboratory (LASL) planned a demonstration of somewhat similar magnitude to that at BNL. The US Department of Energy (DOE) has been supporting both programs, but budget constraints and the judgment that ac SPTL cables will be needed before dc SPTL cables have caused some curtailment of the BNL program and cancellation of the LASL program.

In view of this, the author feels he is placed in a somewhat difficult position, for he has been asked to put forth the case for dc SPTL technology, which to some might seem to be like beating on a dead horse, to others like futilely challenging the collective wisdom of experts, or to still others like exploiting an opportunity to protest in public. On the other hand, because we do believe there is a good case for the dc SPTL cable--that, if developed, it would provide an attractive choice for some significant transmission requirements--we feel obligated to present that case in terms as realistic as possible and thereby, we hope, avoid association with any of the less favorable motives the reader might consider.

Section 2
BACKGROUND

WHY SUPERCONDUCTING LINES?

When certain pure metals, alloys, and intermetallic compounds are cooled to very low temperatures they suddenly, at some critical temperature T_c, lose all electrical resistivity; T_c varies from material to material and has so far been found to be always below 23 K (about -418°F). Such materials are called superconductors because of their resistanceless property. At or just below T_c, only small amounts of current I can be carried in a wire made of a superconductor before it reverts to the normal resistive state at the critical current I_c; but as the temperature T is reduced I_c increases rapidly. For a class of superconductors, called type-II, exhibiting high T_c values, not only does I_c become very large, but the maximum observed current density, $J_c = I_c$ per unit cross section of superconductor in the wire, can be as high as 10^7 A/cm^2.

The quenching of superconductivity in type-II material at I_c is associated with a magnetic field H, which can arise from the self field induced by the transport current, be produced by an applied field, or can result from a combination of self and applied fields. At low fields all magnetic flux is excluded from the interior of the superconductor, which thus exhibits perfect diamagnetism. This condition persists until the field H is increased (at constant T) to some value H_{c1}, at which flux suddenly penetrates into the bulk material as fluxoids, quantized in units $\phi_0 = hc/2e = 2.07 \times 10^{-15}$ T m^2 (or 2.07×10^{-7} G cm^2), where h is Planck's constant, c the speed of light, and e the electron charge. The fluxoid can be roughly pictured as a vortex structure with supercurrents circling about a normal-material core. Now, as H is increased (still at constant T) above H_{c1}, more and more fluxoids enter the bulk, until at H_{c2} they are packed so closely together that the entire volume behaves as if it were filled with the normal vortex cores, and, indeed, the entire material passes into the normal state. The relationship between $J_c(T)$ and $H(T)$ defining the superconductive state is shown in Fig. 2-1 for a typical type-II material.

In the region between H_{c1} and H_{c2}, known as the mixed state, superconducting non-oscillitory transport currents can continue to flow without resistance through the matrix of fluxoids, but only so long as the fluxoids themselves remain stationary. Usually we think of the fluxoids as pinned along their lengths on grain boundaries, crystal imperfections, impurity centers, etc., and held essentially immobile. For a dc transport current of density $\underline{J}$ and a magnetic field of intensity $\underline{B}$, a force $\underline{J}x\underline{B}$ acts on the fluxoids; and if, for instance, $\underline{J}$ becomes large enough that this force exceeds the pinning force, the fluxoids will move and will be ripped away from the pinning sites. Then J_c is exceeded and the flow of current is no longer lossless: dissipative effects due to flux flow or flux jumps appear and are ultimately manifested as heat, related to the work done $(\underline{J}x\underline{B})\cdot\underline{\ell}$, where $\underline{\ell}$ is the distance the fluxoid moves.

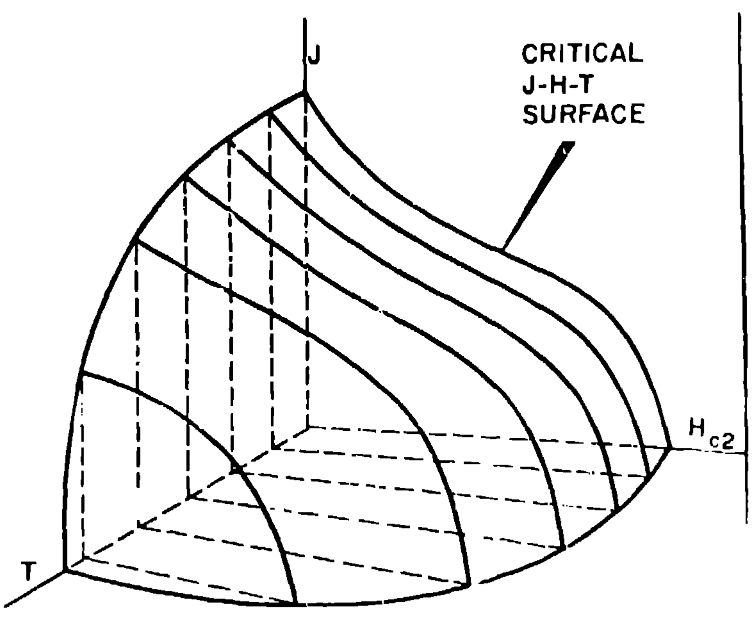

Figure 2-1. Critical current density (J) - magnetic field (H) - temperature (T) surface for a typical type-II superconductor. Region below critical J-H-T surface is superconducting, region above is normal.

To achieve the superconducting state in the laboratory or in a practical device requires the removal of heat, or refrigeration, first, to produce the low temperature environment and, second, to maintain it against thermal inleak from the surroundings and against heating effects, such as fluxoid motion, should they occur. Large (1000 W or more at 4 K) helium refrigerators are available and we are gaining experience in assessing and improving their long-term reliability. But efficiency is another matter. To remove each watt of power (heat) produced at 4 K, even in the ideal (Carnot) case, requires 74 W of compressor power at ambient temperature; in other words the ideal coefficient of refrigeration W(hot)/W(cold) is 74. But in the real world, refrigerators operate on the order of 20% of Carnot, so W(hot)/W(cold) is about 370 for 4 K. At 10 K this is reduced to about 145, and, of course, continues to decrease as T increases. Hence there is strong motivation to operate a superconducting device at as high a T as possible (and still maintain a safe margin for a high current density) and to keep the heat inleak and low-temperature loss-producing effects as small as possible.

We also have stringent requirements for the superconducting material; it must be possible to fabricate the material economically into mechanically and thermally rugged conductors. In addition, it is desirable to use the material with the highest T_c and J_c possible and thereby gain on refrigeration and conductor efficiency. We sometimes have difficulty, however, in simultaneously meeting these materials and performance requirements, for, in general, the higher-T_c materials are more brittle and are less compatible (because of different coefficients of thermal expansion) with normal metal matrices or casings needed to stabilize the superconductor against unwanted excursions into the normal state.

Several mechanisms have been identified as causing loss of superconductor stability, but remedial methods have been devised:

- To surpress flux jumps, the superconductor should be formed of fine filaments (10 μm in diam or less) or in similarly thin ribbons.
- A high thermal conductivity normal metal (Cu or Aℓ) can serve as a matrix to transfer rapidly heat from sites where flux motion occurs to the cryogenic coolant as well as to slow down flux flow.
- To prevent burnout of the superconductor arising from transient effects (current spikes, rapid changes in flux motion, etc.), we can embed the superconductor in a good electrical conductor (again Cu or Aℓ) to carry the current until the transient is removed.

- To decouple superconducting filaments in ac service, to promote current-sharing among filaments, and to decrease eddy-current losses, poor electrical conductivity material can be used to sheath the filaments; in addition, the filaments should be twisted or, preferably, transposed.

For practical purposes, the two most widely used superconductors are the alloy Nb-Ti ($T_c \approx 9.5$ K) and the compound Nb_3Sn ($T_c \approx 18$ K). The former is ductile and can be formed rather readily into a wire of many (100,000 or more) fine filaments in a Cu matrix. But for the more preferable, higher-T_c material Nb_3Sn, the fabrication processes become more difficult; thin ribbons have been made, and reliable multifilamentary (mf) wires are now being developed; but the processes generally involve reaction of Nb and Sn in situ to form the brittle superconducting compound. Work, especially at Los Alamos, is underway to produce acceptable ribbons of Nb_3Ge, the material with highest T_c (≈ 23 K) discovered to date (1). The problems here are more severe than those encountered with Nb_3Sn, but results already achieved are encouraging.

From the above brief background in superconductivity technology, we may easily see what are the principal pros and cons for using superconductors in power transmission cables. On the one hand, we see the possibility of developing high capacity cables which:

- are compact (high J), to reduce land use;
- operate at high I--for a given power capacity, allowing use of lower voltage V than would be the case for a conventional cable and thereby avoiding some difficult electrical insulation and associated environmental problems; and
- can operate with low electric power losses and, therefore, with high efficiency.

But on the other hand, to achieve these advantages, we must contend with:

- the problems of obtaining efficient and reliable refrigeration and thermal shielding over extended distances and time periods; and
- the development of suitable conductors.

Cryogenic technology and the metallurgy of superconductors have both advanced to the stage where the latter two considerations, while still important, present no fundamental limitations against exploitation of the advantages of incorporating superconductors in high capacity cables.

WHY DIRECT CURRENT?

Transmission of dc electrical power has a number of advantages over that of ac power, but during the early growth period of the power industry the dc case suffered a severe set-back. Because line losses go as I^2R, where R is the electrical resistance, it was found economical to increase the power delivery, $P \propto IV$, by increasing V rather than I. The advent of the ac transformer paved the way for voltage increases from the ac generator voltage (25 kV) to the MV range, whereas for dc neither high voltage generators nor transformers are as yet practical. More recently, however, development of inverter-rectifier (converter) technology has provided a means to bypass the dc generator-transformer problem and has opened up the possibility to exploit the advantages of dc transmission. The list of dc transmission systems (mostly overhead) now operating in various parts of the world can be given on a single page, but that list is growing.

The principal deterrent to further use of dc transmission is the cost of the converters needed to change ac to dc at the generator and then back to ac for distribution to the load. For a given power level, the converter cost is fixed, independent of the transmission length between terminals, and can be several times the cost of corresponding ac transmission terminals. Nevertheless, for comparable power loads, dc lines are less expensive than ac lines: two rather than three lines are needed per circuit (for dc, a third less expensive ground return line may be needed); narrower right-of-way and shorter towers can be used; in ac, but not in dc, systems, inductive or capacitive power losses are experienced and require compensation equipment. Thus for short distances ac lines are more economical than dc lines, but at some distance there should be a crossover, where the less expensive dc lines overcome the costs of the more expensive dc terminal equipment. Rules-of-thumb for the industry place this crossover distance at several hundred kilometers for overhead lines and at less than 100 km for underground cables, each instance being sensitive to site parameters and power levels.

On the other hand, there are power system advantages of converters in terms of load flow control and grid stabilization that cannot easily be assigned a dollar value. In several instances large converters have been installed back-to-back, with essentially zero lengths of transmission line between them, to serve as asynchronous ties between pairs of ac systems (the effectiveness of the converters would not be impaired if non-zero lengths of transmission line were installed). Thus there is impetus from several sources to improve converter technology, which, in the longer run, can only mean an expanded use of dc transmission.

The above considerations for conventional dc transmission systems carry over in nearly a one-for-one correspondence to the dc superconducting cable systems. Thus the trade-offs between the dc SPTL and conventional dc cables concern mainly costs, and these are heavily dependent upon system contingency specifications, the length of line needed, and the cost of power. The terminal costs, to a first approximation, should be nearly the same for both dc systems, but cable construction costs per MW-m could be different (and, in fact, in a recent study (2) of high capacity cables, these costs were estimated to be about 50% higher for the installed capacity of the conventional cable compared with the dc SPTL). In addition, the power losses per unit distance for the dc SPTL are likely to be at most half those for the conventional cable, so that as power costs rise there should be an additional favorable bias toward the dc SPTL. However, as a study of long, high-capacity underground dc cables is planned to start in the near future under the auspices of the US DOE, it would be premature to make any detailed predictions about total system costs. Even so, it is important to realize that conventional cable technology is reasonably mature, while dc SPTL technology is not; therefore, more rapid progress in improving designs and decreasing costs can be expected for the dc SPTL case, as indeed has been evident in the past few years.

The trade-offs between the ac and dc SPTLs are, however, more complex and deserve further discussion While these trade-offs will determine the economic cross-over distance for the ac and dc SPTLs, it should be understood that the conventional dc cable is the principal competitor of the dc SPTL in serving power system needs.

LOSSES IN SUPERCONDUCTING CABLES

All cable systems are voltage-limited, and all but the dc SPTL are current-limited. In conventional cables the I^2R losses create heat, which must be removed by conduction to the environment or by some cooling scheme, such as forced flow of fluid (usually oil), so that currents are generally limited to a few thousand amperes. The ac SPTL, while capable of carrying an order of magnitude more than this amount of current, nevertheless, is restricted by ac power losses as the power is increased.

The power losses in the ac SPTL arise from two main sources:

- AC losses in the conductor. While purely ohmic losses in the superconductor are essentially zero (except at joints), the 60-Hz electromagnetic field produces irreversible fluxoid motion and, thus, heat. Theoretically, these hysteretic losses are proportional to J^3 and inversely proportional to $J_c(T)$; therefore, they are expected to rise rapidly with J and as well with T, because $J_c(T)$ decreases with T. In addition to these hysteretic losses in the superconductor itself, eddy current losses might be expected in the normal metal stabilizer (or in any other normal metal structure near the conductor).

- AC losses in the dielectric insulation. The ac field also interacts with the dielectric material of the cable to produce losses that increase roughly as the square of the voltage, are somewhat temperature dependent, but not current dependent.

The dc SPTL, on the other hand does not incur either ac dielectric or conductor losses (negligible but finite losses may arise if the ripple output of the converter is not filtered). Hence, the only losses the dc SPTL would incur are from heat inleak. Cryogenic envelope technology has been developed to the point where enclosures are generally quite efficient, and, of course, can be made more so at a corresponding increase in price. For example, the state of the art can readily produce an envelope for the dc SPTL (as discussed in more detail below) having an average heat inleak all along the line (including joints of envelope sections) of about 0.25 W/m at 10 to 12 K, the operating temperature of the dc SPTL. If this line should carry 7500 MW over a distance of 100 km, this would represent a total loss of 2.5×10^4 W at 10 K, or about $145 \times 2.5 \times 10^4$ W = 3.6×10^6 W of compressor power; the efficiency of this line would then be 99.95% (not including terminal losses or losses in refrigerators on standby for contingency).

An ac SPTL having the same rating and using the same superconductor (Nb_3Sn in this case) would require roughly 2.5 times more refrigeration power to remove heat inleak alone, first, because the operating T would be at about 6.7 to 8.5 K (increasing the refrigeration ratio from 145 to 219), and second, because the cable diameter would need to be about twice that of the dc SPTL (the heat inleak is roughly proportional to the diameter). Both the temperature limitation and the diameter increase arise in large part from ac hysteretic loss considerations.

In the design of an ac SPTL, a reasonable goal is to seek to limit the losses from ac hysteretic effects and from dielectric effects to be each less than the heat inleak losses. Design objectives have been established. The goal for the dielectric loss implies that a material should be sought with a loss tangent of something like 10^{-5} rad or less, which seems possible but is complicated by other requirements that must simultaneously be met by the material. For hysteretic losses, a goal has been set of 10 $\mu W/cm^2$ of conductor surface at a current density of 500 r.m.s. A/cm of conductor circumference, and for Nb_3Sn this condition has been reasonably met at about 8 K. But that current density is only about 20% of what could be used for a dc SPTL at 12 K. Hence, not only is the ac SPTL cable diameter increased because three conductors (for three-phase operation) must be used instead of one (as for the dc coaxial design discussed below), but also because the ac SPTL is restricted by ac losses from carrying as much current per unit cross section of superconductor as can the corresponding dc SPTL.

Requirements for reducing electrical losses in the ac SPTL complicate the cable design, especially in the case of a flexible cable. Flexibility is achieved by winding the conductor as a helix; ac current flowing through such a configuration produces alternating axial magnetic fields, the effects of which can be limited only by constructing pairs of helices of normal and superconducting metals, with the members of each pair wound in opposite senses. Thus the most successful ac SPTL design (3) uses four pairs of helices to reduce eddy current losses. Even here, however, the losses have been measured to be considerably more than the 10 $\mu W/cm^2$ goal.

Dielectric and conductor losses present the most severe challenges to developers of the ac SPTL. We have dwelled at some length on the nature of these problems to highlight the contrast between the complexity of the ac SPTL and the relative simplicity expected of the dc SPTL.

SUMMARY OF COMPARISONS BETWEEN AC AND DC SPTLS

We summarize some general comparisons that can be made between ac and dc SPTL systems when both are rated at the same large capacity, e.g., 10 GW, and both are using the same superconducting material for the conductor.

1. <u>Capital Costs</u>

- Line costs: would be less than half as expensive for the dc SPTL as for the ac SPTL; the cryogenic envelope is a major cost of the cable and, as seen above, is much smaller for the dc SPTL, hence less expensive;
- Terminal costs: would be as much as five times greater for the dc SPTL than for the ac SPTL; but current work in converter equipment promises significant cost reductions.

2. <u>Refrigeration Systems</u>

- Power requirements: considerably less for dc SPTL (higher operating temperature, lower heat inleak, negligible ac losses) than for ac SPTL.
- Helium requirements: between 10 and 100 times less needed for dc SPTL than for ac SPTL.
- Use of hydrogen rather than helium as coolant: possible now (at 13.8 K) for dc SPTL systems and would be more attractive with development of Nb_3Ge material; not possible now for ac SPTL but might be with Nb_3Ge material.

3. <u>Power Losses</u>

- Line losses: negligible for dc SPTL; ac hysteretic and eddy current losses in conductor and ac dielectric losses for ac SPTL.
- Terminal losses: those for dc SPTL are three or four times larger than for ac SPTL; again, work on converters could reduce the disparity, perhaps down to a factor of two.

4. <u>System Considerations</u>

- Network stability: converters of dc SPTL enhance stability and control.
- Fault protection: converters provide some protection against power surges for dc SPTL, where current spikes may reach a maximum of 1.5 to 2 times normal currents; ac systems must be designed to accommodate current spikes 10 to 15 times normal currents.
- Other limitations: the dc SPTL has no constraints such as load flow, short-circuit current level, or need for reactive compensation; excess capacity can readily and inexpensively be built into the dc SPTL.
- Reliability: the dc SPTL design is far less complex than that for the ac SPTL; similarly its construction should be correspondingly simpler; thus the dc SPTL should inherently have a higher reliability.

- Environment: the dc SPTL coaxial design provides for complete cancellation of electric and magnetic fields; the ac SPTL can also be designed to accomplish this; both ac and dc SPTLs are compact and can be placed underground.
- Use: the ac SPTL, not requiring expensive terminations is well adapted to shorter-distance, high-capacity situations, which are likely to occur before the need for longer-distance missions, where the dc SPTL would see service.

Section 3
DC SUPERCONDUCTING CABLE CONFIGURATIONS

COAXIAL DC SPTL DESIGN

The LASL dc SPTL Program has developed the coaxial design (4,5,6) shown in Fig. 3-1. This cable has the advantages of simplicity plus the self-containment of complete electrical and cryogenic cooling circuits. For the electrical circuit, the inner conductor (mf Nb_3Sn stabilized in Cu) is wound over a spiral tape former and could be of either positive of negative polarity; wrapped tape dielectric separates the inner and outer conductors, the latter being also mf Nb_3Sn wire but electrically neutral. For the cryogenic cooling circuit, helium at, typically, 16 atm and 10 K, is passed down the inside of the spiral former to a remote expander, where the fluid arrives at conditions of approximately 14 atm and 12 K and leaves at 8 atm and 10 K; from the expander, the fluid returns to the refrigerator passing through the annulus formed by the outside of the armor surrounding the outer conductor and the inside wall of the cryogenic enclosure. The enclosure itself is

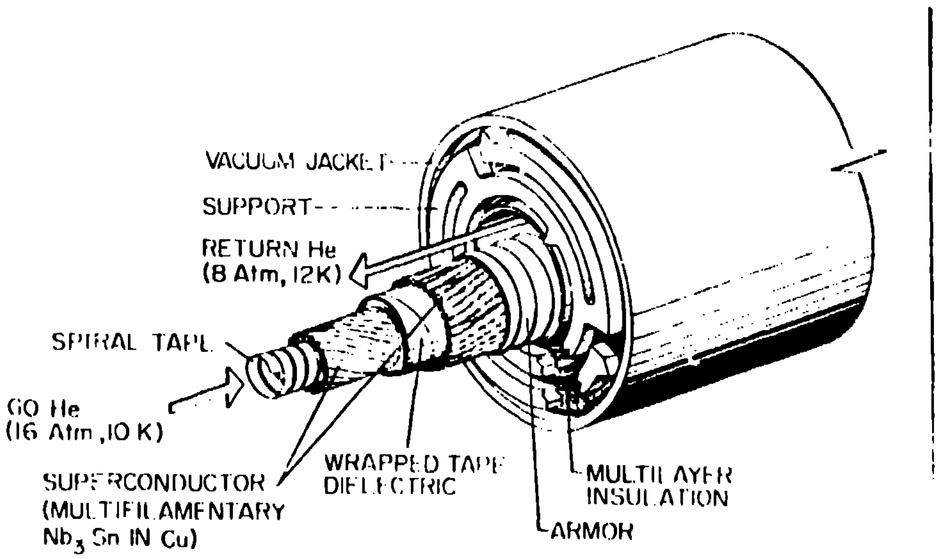

Figure 3-1. Coaxial dc SPTL cable design.

composed of two concentric pipes with the space between evacuated of gases but containing wrapped layers of thermal insulation (thin aluminized sheets of Mylar).

The construction of a coaxial dc SPTL could proceed with the laying in trenches of 20- to 30-m lengths of factory-fabricated cryogenic envelope and then joining these lengths in the field. The flexible cable would also be factory-fabricated, in lengths up to 300 m, then drawn through the in-place cryogenic envelope and joined to adjacent lengths. Refrigerator spacing could vary from 5 to 30 km or more, depending on the specific transmission situation; remote expanders would be placed roughly half-way between refrigeration stations. A schematic for this system is shown in Fig. 3-2.

A considerable advantage of this coaxial cable design lies in its flexibility with respect to the voltage, current, and power specifications. Depending on the system requirements and various cost trade-offs, power delivery above 3 GW could be accommodated by voltages between 25 and 500 kV and by currents from 10 to 100 kA or more; the basic configuration shown in Fig. 3-1 could be maintained, but the relative and overall diameters would be changed for each different voltage-current requirement. To appreciate the sizes involved, we could construct a 7.5-GW line operating at 300 kV and 25 kA to be enclosed in a 34-cm diam outer pipe.

Figure 3-2. Schematic layout showing typical sequence and spacing of elements of dc SPTL refrigeration system.

An additional advantage of this design arises from the two concentric conductors carrying the same current but in opposite directions: all electric and magnetic fields are cancelled to produce zero net fields outside the cable, thus completely eliminating objectionable environmental effects usually associated with high capacity power transmission systems.

DOUBLE MONOPOLE DC SPTL DESIGN

Two problems associated with the coaxial design have led us to consider other dc SPTL configurations. The first of these problems is technical in nature and concerns the properties of dielectric materials under constant dc stress, as well as polarity reversal, at low temperatures. This is not a problem in the sense that we foresee difficulty in satisfying the cryogenic dielectric needs of the dc SPTL but rather is one requiring time and effort to research the situation, to understand the limiting features of the dielectric system, and to select the optimum materials. Work in this area has been started at LASL; and while initial results are encouraging, there is still much to learn, so that cable performance estimates are not based on long-term experience. The second problem relates to power system economics, especially when contingency requirements increase the number of circuits needed for a given transmission situation. In the case of a recent study (2) of systems to carry 10 GW, a single coaxial dc SPTL could have been designed to transmit the needed power; contingency requirements (first contingency: continue at 10 GW; second contingency: continue at 7.5 GW for 4 h), however, dictated the proposal of three cables, each with 7.5-GW capacity. In other words, 22.5 GW of capacity was needed for a 10-GW power load.

To reduce the impact of these problems, we consider a double monopole design. Here two identical lines (poles) are needed to complete the electrical and cryogen flow circuits; a schematic of one of these is shown in Fig. 3-3. The armor (corrugated Cu tube) surrounds the conductor (again mf Nb_3Sn in Cu) and also forms the inside wall of the cryogenic envelope. The outer wall of the envelope could be a smooth tube or could be (as in Fig. 3-3) corrugated for flexibility, with the corrugations filled to present a smooth surface (conducting layer) for the covering of dielectric material. A significant advantage here is that the dielectric would be at ambient temperature and could be constituted identically to that of conventional cables, thereby eliminating any problems that might be associated with cryogenic dielectrics.

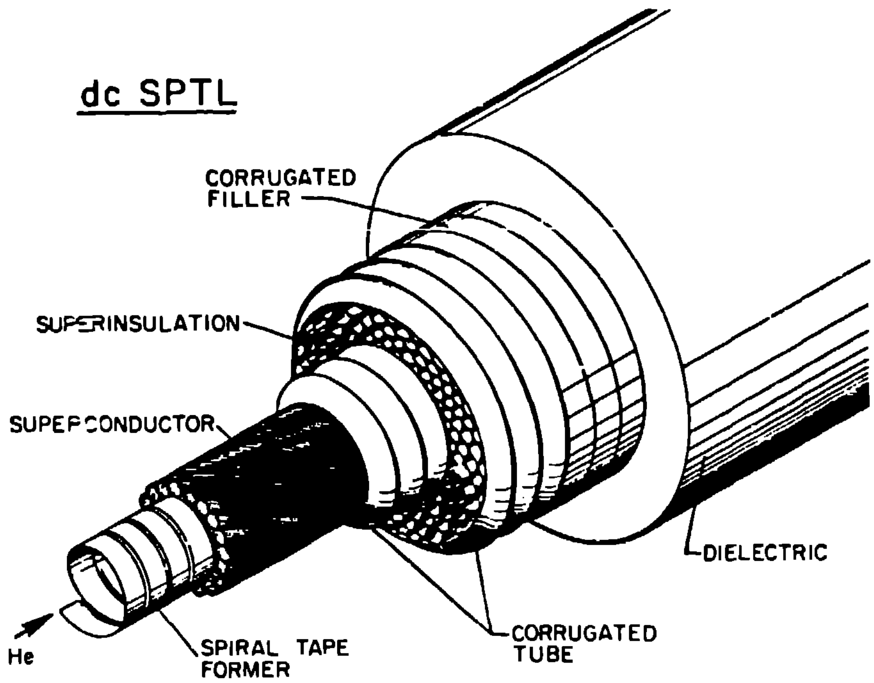

Figure 3-3. Schematic of a possible design for one pole of a double monopole dc SPTL. Other superconductor configurations can be considered and the outer tube could be smooth rather than corrugated.

The current carrying capability of each pole could reasonably be as high as 8.5 kA and the voltage standoff as high as 600 kV: thus, a bipolar pair could carry more than 10 GW. However, for the 10-GW mission, together with its contingency requirements as mentioned above, it would be possible to have three bipolar systems, with each pole normally carrying 2.5 GW (say, 450 kV at 5.6 kA), for a total capacity of 15 GW, 7.5 GW less than the coaxial design capacity (under second contingency conditions this system could carry the full 10 GW). The outside diameter of the cryogenic envelope of each pole of such a line would be less than 12 cm, and the heat inleak could reasonably be reduced to 0.15 W/m. In addition, the cost of the six small monopolar lines might be reduced compared to that of three coax lines each roughly three times larger in diameter. Also, longer lengths of the cable and envelope construction, which is far less complex than for the coaxial design, could be accomplished in a factory rather than in the field; and machines are already available for encasing the conductor in a corrugated cryogenic envelope in one continuous operation.

One disadvantage of the double monopole line, as compared with the coaxial line, is that the electric and magnetic fields are not cancelled; but this should produce no more undesirable environmental effects than would be encountered with a conventional 450-kV dc cable system.

Other dc system requirements that must be considered are switches and/or circuit breakers at the converter terminals. These have not yet been developed for such high power systems but should be more readily attainable for the considerably lower currents carried in the double monopole line vis-a-vis the coaxial line.

Section 4
PRESENT STATUS OF DC SPTL DEVELOPMENT

INTRODUCTION

Development programs of dc and ac SPTLs have, of course, several common elements, particularly those concerned with refrigeration and thermal insulation. However, there are numerous areas where different approaches must be taken, especially with regard to dielectric insulation, cable terminations, conductor design and development, and systems analysis. Work in all these areas has been pursued on dc SPTL systems at LASL and has been carried to a point of design maturity where the individual elements could be assembled into a model cable. In this section we briefly discuss the present status of development of each of these areas for the dc SPTL.

REFRIGERATION AND THERMAL INSULATION

A program combining calculations with experiments has been carried out to determine cool-down, steady state, and thermal upset recovery conditions for the flow of cryogenic helium in a dc SPTL. Calculations of the dynamics of the thermal and fluid transport for unidirectional flow, as would occur in the double monopole system, have been verified in a scaled (1:10) model system for a transmission cable connected to a refrigerator. For bidirectional (countercurrent) flow, equilibrium calculations have been made of the temperature profiles in the two flow paths as a function of length. These results have been checked in a full-scale cryogenic flow loop using a 17-m long commercial cryogenic enclosure housing a conventional self-contained oil-filled cable (with He flowing in the central channel ordinarily occupied by oil) and fitted with a far-end expander. Cool-down and steady-state experiments have been performed with this cable, which has thermal properties similar to the coaxial dc SPTL. Calculations of the dynamic properties of such a system are underway. We feel that the general behavior of the unidirectional and bidirectional systems is well understood but that more work is required to clarify some details of operation to ensure reliability.

In order to optimize the refrigeration of cables, we must consider trade-offs when the refrigerator and cable function as an integrated system. This is especially true in the bidirectional flow case where the cable acts as the final heat exchanger of the refrigerator. Extensive studies have been made at LASL to calculate refrigerator performance of several refrigeration cycles as a function of such system parameters as: refrigerator spacing, cryogenic enclosure inside diameter, thermal input to the refrigerant, temperature increase along the cable, inlet temperature and pressure, compressor suction and discharge pressures, and pressure drop along the cable. The results can be used to predict optimum operating conditions and cable geometry specifications, which must then be studied for cost effects.

DIELECTRIC INSULATION

DC high-voltage breakdown tests have been performed on thin-sheet samples of about 15 promising dielectric materials under conditions of varying temperature (12 K, 18 K, 83 K and 293 K) and He pressure (0.69 MPa and 1.38 MPa, i.e., 7 and 14 atm). These tests were used to select three or four of the most promising materials (cellulose paper, copaco paper, and composites of cellulose paper and Mylar and of cellulose paper and Pink Poly), which were then obtained as 2.5-cm wide tapes and wound onto mandrels simulating cable samples. The mandrels hold 19 or more layers of 0.075-, 0.10-, or 0.125-mm thick ribbons wound to a total thickness of 2.8 mm. Tests of breakdown under impulse, steady state, and polarity reversal conditions are still in progress, but initial results of breakdowns in the 90-100 kV range (stresses of 32 to 36 kV/mm) are encouraging.

CABLE TERMINATIONS

Cryogenic terminations for dc cables are not commercially available but must be developed. The design of these terminations must take into account, first, minimization of heat leak and, second, minimization of the effects of different thermal contraction of parts made from different materials. Additional difficulties arise because these constraints may conflict with the requirements of high-voltage operation. Finally, the high-voltage bushing must be combined with high-current leads to form the complete termination.

For the dielectric screening tests we have developed a nominal 100-kV bushing fabricated primarily from cast epoxy. This bushing has survived more than 40 thermal cycles between liquid nitrogen and room temperatures and an additional 50 cycles to helium temperatures. Tests with high voltage indicated that negative polarity gives the poorest results. At the -100-kV level, occasional corona activity is observed; at -200 kV, corona is continuous; and after the -223 kV level is held for 10 minutes, the temperature and pressure of the cryostat rise rapidly, indicating corona inception in the helium space between the center conductor of the bushing and the cryostat wall.

For cable tests we are developing a larger, horizontal cryostat and a 300-kV epoxy-Mylar bushing. The weather skirts of this bushing are cast epoxy, and the dielectric between the center conductor and the ground plane is made up of layers of 0.254-mm Mylar separated by 0.178-mm layers of epoxy. The purpose of the Mylar in the epoxy is to relieve the electrical stress in the epoxy, a concept demonstrated in tests of our smaller model epoxy-Mylar bushings. The dielectric constant k of epoxy is 7, while for Mylar k=3, hence the electric stress is concentrated in the Mylar, which has the higher breakdown strength. Calculations show that the electric stress on the first layer of epoxy adjacent to the high-voltage inner conductor will be 7.87 kV/mm instead of 13.63 kV/mm as would occur if only epoxy or Mylar were used. The design of this bushing has several advantageous new features:

- The composite construction permits a smaller cross section than would otherwise be possible, thereby reducing heat leak into the Dewar and easing the casting problems.
- The Mylar wrap prevents radial cracks in the body of the bushing.
- The casting of the ground-potential electric-stress shield from polyurethane foam, instead of machining it from glass-epoxy laminate (G-10), will relieve shrinkage and thermal stress in the epoxy around the stress shield.
- The inner conductor is lined with polyurethane foam to isolate thermally the inner wall of the bushing, thereby reducing the thermal gradient from the cold inner wall to the room-temperature outer wall of the bushing.

We have made generalized calculations for the design of vapor-cooled high-current leads. A set of nominal 5-kA leads has been constructed and installed in the 17-m cryogenic flow loop for conductor tests now in progress. These leads have been run at up to 20% over rating, cooled by 10 K He gas directly from the refrigerator (the He is returned to the refrigerator in a closed loop). The performance was as predicted by the calculations. Higher capacity leads can be made by bundling the elements of the 5-kA design. Because this design gives rise to very compact units in the radial direction, high-current elements (e.g., 25 to 50 kA) could be fitted into the core of the high-voltage bushing to complete the termination.

CONDUCTOR DESIGN AND DEVELOPMENT

Commercial superconducting wire manufacturers have collaborated with us to produce mf Nb_3Sn conductors with properties specifically suited to dc SPTL service, requiring stable operation (i.e., resistance to flux jumps and rapid recovery of the superconducting state following unwanted excursions to the normal state) with the highest possible J at 14 K: our goal of $10^5 A/cm^2$ of superconductor at 14 K and 0.5 T (5,000 G) has been met. The wire fabrication begins with packing 37 Nb tubes filled with bronze (Cu, 13 weight percent Sn) rods into a pure Cu billet, which is extruded and drawn to achieve a final diameter of 1 mm or 0.5 mm. The wire is then heat-treated to react the Sn in the bronze with all of the Nb. The proper conditions for the heat-treat are critical to prevent Sn from diffusing into the pure Cu and thereby destroying the good thermal and electrical conductivity of the Cu. Our experiments to determine the optimum heat treat conditions indicated a temperature of 750°C for 64 h. The amount of normal metal stabilizer needed has been determined from a number of experiments involving normal zone propagation as a function of T and J.

Because the wires when reacted are brittle but still must withstand pretty rough handling and sharp bending during the cable manufacturing process, bend and tension tests were performed to determine the amount of mechanical strain the wires could tolerate before J_c degrades. The results indicate that J_c actually first increases under up to 0.7% strain before degrading and that the wire can be safely handled in the cabling machinery.

The J_c of a single wire also degrades when it is bundled with other current-carrying wires because of the magnetic field created by the other wires. For example, calculations and experiments show that the critical current carried by a bundle of seven wires is only about 70% that of the sum of seven isolated wires. In addition, studies of the relative stabilizing effectiveness of Cu when co-drawn with the superconductor as compared with merely being laid next to the superconductor in a tight cable indicated that the latter condition was entirely satisfactory. This would allow a smaller amount of Cu to be used in the original billet and, thus, a substantial reduction in the cost of producing the conductor. By understanding the geometrical effects of J_c degradation and of stabilization by Cu, we can arrive at the most effective yet least expensive configuration for the conductor. For general dc SPTL purposes this could be a 19-strand cable, with the inner 7 strands pure Cu and the outer 12 wires with perhaps a Cu:superconductor ratio of 5:1. Wires of this sort are being studied in the cryogenic flow loop test facility.

SYSTEM STUDIES

It is one matter to design workable elements of a dc SPTL and another to combine them into a system which will operate successfully in the power grid. To ensure this success we must first perform the most complete and careful systems studies possible. These involve investigations of electrical characteristics: fault currents, over voltages, terminal (converter) configurations, power start-up; system refrigeration: cooldown, shut down for maintenance or replacement, reaction to and recovery from thermal upsets; cost analysis: materials, labor, capitalized power losses, estimates for new fabrication techniques and for new technologies. We have gained considerable experience in these areas and have been engaged in a number of studies which require continual updating and revision. Nevertheless, the conclusions to date indicate that no technical barriers exist to prevent the use of the dc SPTL and that ways are continually being found to enhance the efficiency and cost-effectiveness of the dc SPTL system.

Section 5
CONCLUSIONS

As stated at the outset, superconducting transmission systems will find use only in situations demanding high capacity circuits, where SPTLs should have distinct advantages over conventional systems. However, it is clear that these attributes are not sufficient by themselves to motivate electric utility planners to consider high capacity lines; SPTLs cannot be the driving force for such a trend, but their characteristics should be sufficiently well known or predictable so that when such a trend develops, as we believe it will, they could be put into service to enhance the effectiveness of high capacity systems. Under expected conditions both ac and dc SPTLs should be useful for providing efficient and cost effective power transmission in their respective areas of advantage--ac for the shorter routes and dc for the longer routes. Even if requirements for these do not develop for several decades, it is not too soon to hone the technology, both because many years of working experience will be demanded of this technology to prove reliability and because new ideas for improving SPTLs have been emerging at a healthy pace. The technology is young and promising and should be allowed a chance to grow; if given that chance, in all probability it will produce some pleasant surprises.

At present, the hopes expressed here hang entirely on one US program, the ac SPTL Program at BNL. We at LASL cannot deny our chagrin at being stopped from developing the dc SPTL or our strong feelings that the dc SPTL, being far less complex than the ac SPTL, has the better opportunity to demonstrate the reliable use of superconductivity in power transmission systems; nevertheless, we wholeheartedly support the efforts of the BNL Program. With only one contender remaining in this kind of race, all bets must be placed on that contender to finish successfully. If it fails to do that, interest in reviving and rerunning the race may be a very long time away, if ever. Such an outcome would, of course, be disastrous for superconductivity technology, but also, we feel, a disservice to the electric power industry.

Meanwhile, we feel it is important to continue research on areas that could improve the performance and the cost-competitiveness of the dc SPTL as well as the ac SPTL. In particular, the aspects of higher temperature operation, using H_2 rather than He as a coolant, are intriguing and promising. This requires the further development of Nb_3Ge, or other high-T_c conductors, as well as of dielectric materials with appropriate characteristics (the latter is, of course, not necessary for the double monopole dc SPTL). It should be possible to operate a SPTL effectively with "slush" hydrogen (a mixture of solid and liquid at the freezing point near 13.8 K) using the latent heat of fusion to absorb any heat production or inleak and thereby maintain isothermal conditions in the line. More efficient, more reliable refrigeration methods would also be a boon to all superconducting technologies, including transmission lines. Both the Electric Power Research Institute and the US DOE have recognized these needs for advanced developments, and we are naturally pleased that they have encouraged us to pursue some of these topics at LASL.

Section 6
REFERENCES

1. M. P. Maley, L. R. Newkirk, J. D. Thompson, and F. A. Valencia, "Development of Nb_3Ge for Power Transmission Applications," EPRI EL-965, Project 7355-1, Final Report, Jan. 1979.

2. "Evaluation of the Economical and Technical Viability of Various Underground Transmission Systems for Long Feeds to Urban Load Areas," U.S. Department of Energy, HCP/T-2055/1, Dec. 1977.

3. M. Garber, "A 10-m Nb_3Sn Cable for 60 Hz Power Transmission," IEEE Transactions on Magnetics, Vol. MAG-15, No. 1, Jan. 1979, pp. 155-158.

4. J. W. Dean and H. L. Laquer, "Conceptual Design of a DC Superconducting Power Transmission Line," Proc. 1976 Underground Transmission and Distribution Conf., IEEE Publ. No. 76-CH 1119-7-PWR, 1976, pp. 417-424.

5. H. L. Laquer, J. W. Dean, and P. Chowdhuri, "Electrical, Cryogenic and Systems Design of a DC Superconducting Power Transmission Line," IEEE Transactions on Magnetics, Vol. MAG-13, No. 1, Jan. 1977, pp. 182-187.

6. P. Chowdhuri and F. J. Edeskuty, "Bulk Power Transmission by Superconducting DC Cable," Electric Power Systems Research, Vol. 1, 1977/78, pp. 41-49.